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New Calculating method for HCM 2000 Queue Length Estimation Procedures with the Application of Floating Car Data

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Abstract

The maximum back of queue length (MBQL) is one of the measures of effectiveness (MOEs) for signalized-intersection level of service analysis. The Highway Capacity Manual 2000 (HCM 2000) proposes a queue length calculation model, based on the Akcelik's queue model, which was developed in the 1980's, has stood the test of time as a fundamental method of traffic signal analysis. The HCM 2000 model is comprised of two terms that the first term is determined by assuming a uniform arrival pattern and the second term is associated with randomness of flow and overflow queues. However, the application of the HCM 2000 is limited as the initial queue length needs to be known at the start of analysis period for the second-term model.

Using data of floating cars and loops, the authors have developed an alternative calculating method without initial queue length information for the HCM 2000 second-term queue length model. The experiment carried out at an intersection in Shanghai, China shows that the developed method can provide more accurate estimation of the queue length than HCM 2000. The later a floating car arrives in the queue, the more accurate estimation can be obtained. The proposed method is easy to understand and can produce results more reliable and accurate in citywide intersections evaluation.

Keywords: HCM 2000, queue length model, new calculating method, floating car data.

1. Introduction

Several measures of effectiveness (MOEs), including delay, number of stops, fuel consumption, emissions, and queue length, are associated with the queuing process at signalized intersections. Queue length is an important MOE because queues which overflow the available storage space have an adverse effect, such as spillback and storage blocking on the overall operation of the intersection.

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Several methods which were used to calculate the queue length have been developed since the sixties by Webster(1958); Roberston(1969); Newell(1971); Catling(1977); Kimber(1979); Vigos(1979); Akcelik(1999); Henry Liu(2009). However, no method had produced results reliable and accurate enough to market to city-run intersection assess.

Queue length calculation model in Appendix G in Chap.16 of the 2000 Highway Capacity Manual (HCM 2000), developed by Akcelik, is probably used most for practical applications. The queue length model is comprised of two basic terms:

- "The First Term" (Q_1): is the average back of queue, determined firstly by assuming a uniform arrival pattern and then adjusting for the effects of progression for a given lane group.
- "The Second Term" (Q_2): is an incremental term associated with randomness of flow and overflow queues that may result because of temporary failures, which can occur even when demand is below capacity.

Q_1 represents the number of vehicles that arrive during the red phase and during the green phase until the queue dissipates. Q_2 represents the average overflow queue caused by temporary control failure of signal. The input data that the HCM 2000 queue model requires are lane group information, flow rates, capacities, the proportion of vehicles arriving on the green and initial queue at the start of the analysis period. The initial queue, required in the second term (Q_2), should be observed in the field. However, if field information is not available, successive period analyses, beginning with a period in which there is no initial queue, can be performed. By now, manual observation is the only observing way to get the initial queue length.

If the start of the analysis period is at the beginning of the red phase of a signal cycle, the initial queue is equal to the overflow queue of the last cycle. The overflow queue is queued vehicles left over a green phase at a signalized intersection. To calculate the expected value of the overflow queue, used in Beckmann's and Mcnell's formulas, Miller's (1968) formula represents one of the most popular expressions:

$$E[Q_0]=\frac{\exp[-1.33*\sqrt{s*t_g*(1-x)/x}]}{2*（1\text{-x}）} \tag{1}$$

Akcelik (1980) provided a continuous formulation of the queue evolution using the coordinate transformation technique:

$$\mathrm{Q(T)}=\frac{\mathrm{cT}}{4}[\mathrm{x}\text{-}1+\sqrt{(\mathrm{x}\text{-}1)^2+\frac{12(\mathrm{x}\text{-}\mathrm{x}_0)}{\mathrm{cT}}}] \tag{2}$$

x_0=0.67+Sg/600 is the limit value of the degree of saturation above which the stochastic effects are relevant. The two formulas above are the most used models assuming that initial queue of the last cycle is zero.

Viti and van Zuylen (2004) have proposed a heuristic analytical formulation of the expectation value of the overflow queue in time using Poisson arrivals, which assumed that any initial queue value of the last cycle can be observed artificially.

In summary, the initial queue is a key parameter for the queue estimating model in HCM 2000. The queue model proposed in HCM 2000 will fail to address the situation if the initial queue value is not available. The application of the HCM 2000 queue length model is limited because there is no automatic observation method except manual observation for the initial queue.

The paper develops an alternating calculating method of HCM 2000 queue length estimation procedure with the application of floating car data (FCD). As the new model does not require any information of initial queue, it can estimate queue length of intersections dynamically. The proposed method is easy to understand and can produce results more reliable and accurate to market to the scope of city.

The article is organized as follows: Section 2 introduces the problem statement and the notation. Section 3 describes the new calculating method for the queue length estimation. The implementation of the proposed method and the result analysis are presented in Section 4. Lastly, Section 5 summarizes the findings and results.

2. Problem statement and notation

Table 1 lists the parameters used in the following paper.

Table1. Parameters used in the following paper

Variable	definition
D_i	the state of a floating car arriving during the red phase
q_i	the location of a queuing floating car in terms of number
t_i	the arriving time of the floating car
r_i	effective red time (s)
g_i	effective green time (s)
C_i	cycle length (s)
$r_i^{'}$	the adjusted effective red time (s)
$C_i^{'}$	the adjusted cycle length (s)
Q_m	the maximum back of queue (veh)
$Q_m^{'}$	the adjusted maximum back of queue (veh)
$Q_1^{'}$	the adjusted first-term queued vehicle (veh)
$Q_2^{'}$	the adjusted second term of queued vehicles, estimate for average overflow queue (veh)
Q_{bL}	initial queue at start of analysis period (veh)
PF_2	adjustment factor for effects of progression
v_L	lane group flow rate per lane(veh/h)
x_L	ratio of flow rate to capacity (v_L/c_L ratio)
k_B	Second-term adjustment factor related to early arrivals
c_L	Lane group capacity per lane (veh/h)
T	Length of analysis period (h)

The second term of the average back of queue in HCM 2000 is computed using the Equation (3):

$$Q_2=0.25c_LT[(X_L-1)+\sqrt{(X_L-1)^2+\frac{8k_BX_L}{c_LT}+\frac{16k_BQ_{bL}}{(c_LT)^2}}] \quad (3)$$

Actually, the value of Q_2 can be an approximate cycle overflow queue when there is no initial queue at the start of the analysis period. However, the initial queue at the start of the analysis period is also accounted for in Q_2 . The contribution of the second term (Q_2), the portion of the queue that results from random arrivals and

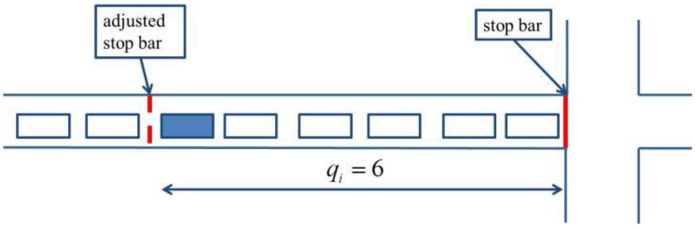


Fig.1. Snapshot of an intersection right before the red interval terminates.

overflow queues, grows proportionally as the arrival flow increases. So the initial queue should not be ignored especially when the traffic is heavy. As no method except manual observation can be used to get the initial queue, the method in HCM 2000 is not for the real-timed and large-scale intersection queue estimation. Using the floating car data generated by the globe positioning system (GPS), which is installed in taxies, we develop a practical computing method based on the method in HCM 2000. The next part presents the information of FCD.

Fig 1 illustrates a snapshot of traffic at a signalized intersection approach at the end of a red phase. Rectangles represent queuing vehicles, while solid rectangles represent floating cars. The main objective is to estimate the maximum back of queue length Q_m , if the queuing state of floating cars in the queue is known. It is assumed that the distance of floating cars from the stop bar and the arrival time can be calibrated by location tracking technologies.

For simplicity, the location of queuing vehicles is measured in terms of the number of vehicles. For example, in Fig 1.there is a floating car and the location of the probe, q_i , is 6. It is noted that the model are developed for vertical queues as is shown in Fig 1. With today's GPS technology (GPS systems which can provide one to three meter accuracy (USDOT, 2008), the location of the floating car can be observed. Then the number of vehicles in front of the probe can be measured by selecting the average vehicle length to be representative of different vehicle types. The Code for Planning of Intersections on Urban Roads of the People's Republic of China, enacted on December, 24, 2010, gives a vehicle size standard. Other details about the state of a floating car, such as its speed, acceleration and deceleration, are ignored in this paper. Furthermore, this paper does not deal with information of flow characteristic and the data of the queuing process.

3. Methodology

A signal cycle is selected as the analysis period which begins at the start of a red phase. The queue at the start of a red phase is the initial queue which can also be regarded as the overflow queue of the last cycle. Although 15-min period is recommended in HCM 2000, it is still reasonable to choose a 3-min cycle as an analysis period, because it is easier to know the situation of intersection cycle to cycle.

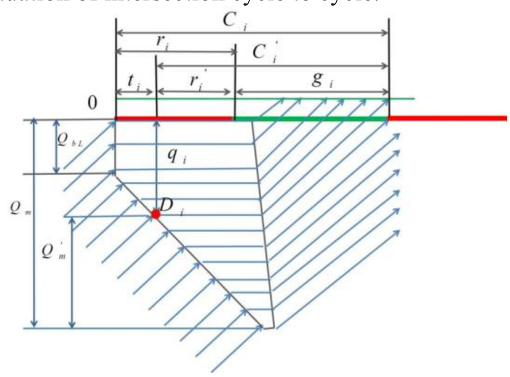


Fig.2. Cycle maximum back of queue

If a floating car arrives in the queue during the red phase, the state of the car will be recorded as $D_i(q_i, t_i)$. The distance of the floating car from the stop bar in vehicles is q_i and t_i is the time when the car stops at the back of the queue. Then the analysis cycle C can be divided into two parts, t_i and the residual time $C_i^{'}$ ($C_i^{'} = C - t_i$), as is shown in Fig 2. During $C_i^{'}$ more vehicles from the upstream intersection will accumulate at the back of the floating car. The $C_i^{'}$ can be regarded as an adjusted signal cycle with a zero initial queue and the stop bar is adjusted to the back of the floating car. This can be explained through an example case illustrated in Fig 1. In Fig 1, $Q_m = 8$, $q_i = 6$, and the vehicles at the back of the floating car are two. Then the adjusted effective red time and effective green time can be represented by $r_i^{'}$ and $g_i^{'}$ respectively. The arriving time of a floating car t_i, is the adjusted start of the red phase. As the car arriving during the red phase, the adjusted red time $r_i^{'} = r - t_i$ while the adjusted green time is equal to the green time of the analyzing cycle. Only the floating cars arrive in the red phase can be used to compute the queue length.

The adjusted maximum back of queue, $Q_m^{'}$, during the adjusted signal cycle, is just the cars accumulating after t_i, shown in Fig 2. The relation between the maximum back of queue Q_m of the analysis cycle and the $Q_m^{'}$ can be expressed by:

$$Q_m = Q_m^{'} + q_i \tag{4}$$

As the q_i is known, the Q_m can be derived by computing the $Q_m^{'}$. Based on HCM 2000, the $Q_m^{'}$ can be calculated as follows:

$$Q_m^{'} = Q_1^{'} + Q_2^{'} \tag{5}$$

The first term is calculated using equation (6) as Equation G16-7 in HCM 2000.

$$Q_1^{'} = PF_2 \frac{\frac{V_L}{3600}(1 - \frac{g}{C})}{1 - [\min(1.0, X_L)\frac{g}{C}]} \tag{6}$$

$Q_1^{'}$ represents the number of vehicles which arrive during the adjusted red phase and during the green phase until the queue dissipates.

Equation (7) is used to compute the second term of the average back of queue with a zero initial queue.

$$Q_2^{'} = 0.25 c_L T[(X_L - 1) + \sqrt{(X_L - 1)^2 + \frac{8k_B X_L}{c_L T}}] \tag{7}$$

$Q_2^{'}$ represents the average overflow queue caused by temporary control failure of signal.

An alternative computing method of HCM 2000 queue length model is proposed in this paper. The developed method has the same assumption and limitation.

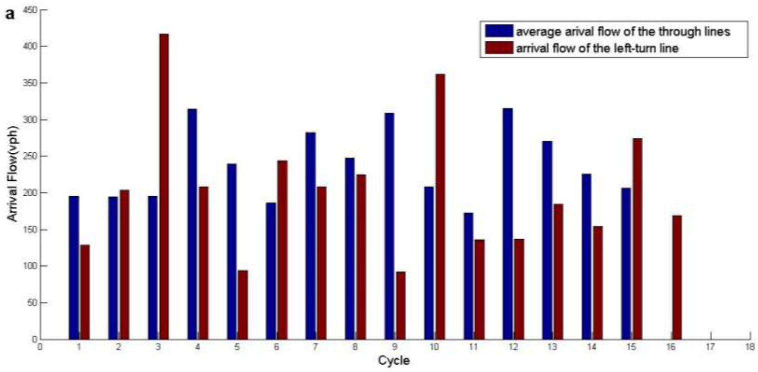
4. Implementation

4.1. Data collection

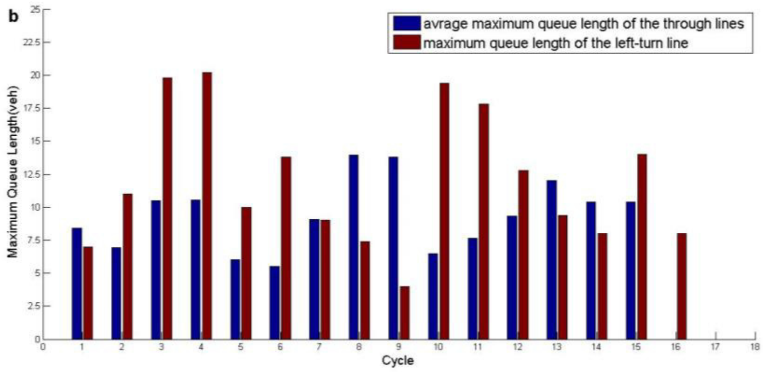
In this study, on July 24, 2012, an observation was taken in the northbound entering approach of the intersection of Middle Yan'an Road and Huashan Road, which is one of the busiest intersections in Shanghai. Different floating cars were designed to arrive into the approaches in different time during the analysis period. Two SONY HDR-CX180E HD Video Cameras were used to record the observation which lasted for an hour. Table 2 lists the variables collected in the field with brief descriptions.

Table 2 Intersection Related Variables with their Descriptions, and Means

Variables	Description	Observation source	Mean
Number of through lanes	Number of through lanes for all entering approaches	SCATS in Shanghai	3
Number of right-turn lanes	Number of right-turn lanes for all entering approaches	SCATS in Shanghai	1
Number of left-turn lanes	Number of left-turn lanes for all entering approaches	SCATS in Shanghai	1
Cycle length	Cycle length(sec)	SCATS in Shanghai	189
Total arrival flow per cycle on the through lanes	The total flow arriving in each cycle(veh)	Loop detectors	12.40
Total arrival flow per cycle on the through lanes	The total flow arriving in each cycle(veh)	Loop detectors	11.35
The actual MBQL per cycle on the through lanes	The actual MBQL during each cycle(veh)	Videos	9.40
The actual MBQL per cycle on the left lane	The actual MBQL during each cycle(veh)	Videos	11.38



(a) Arrival flow



(b) MBQL

Fig 3. Camera data: (a) flow profiles; (b) queue length profiles.

The through and left-turn approaches are selected for analysis as there is no signal control for the right-turn approach. Fig 3.shows the arrival flow and MBQL for through and left-turn in each cycle observed with the cameras. The through lines had more stable arrival flow and MBQL than the left-turn line during the analysis period. The average arrival flow of the through lines ranges from 195 to 315 vph while the left-turn line's arrival flow is from 90 to 420 vph. The average MBQL of the through lines varies from 5.5 to 10.5 veh, and that of the left-turn line fluctuates from 4 to 20 veh. As the model in HCM 2000 is restricted to the situation when arrival are assumed to follow a specific distribution function (e.g., Poisson) and to have stationary average rates(Viti & Van Zuylen(2004)), the through lines seem to get more reasonable calculating results.

Comparing Part (a) and Part (b) of the figure we see that there is positive correlation between the arriving flow and the MBQL. This correlation has been demonstrated by queue length models(Webster(1958); Catling(1977); Akcelik(1999)).

Floating Car Data (FCD) database consists of a great number of GPS point records and the information such as vehicle ID, latitude and longitude, time can be recorded. Then, based on a Geographic Information System (GIS) map, the FCD was filtered for each selected road. Considering the driving route of vehicles, floating cars can be matched for each approach. With the signal control features extracted by the video, the arriving state of different floating cars can be obtained.

4.2. Analysis results

The data collected from loop and FCD is used to estimate the MBQL, and the estimated values are compared with the ground truth data, which is recorded by cameras (the MBQL for each cycle is manually extracted by watching the videos). The model from HCM2000 is used to estimate the MBQL at the start of each cycle when the initial is observed from the videos. With the FCD, the MBQL can be estimated at different time by applying the method developed in this paper. As event-based data are collected by detectors, two models (HCM2000, new methodology) can be tested. The Absolute Percentage Error (APE) of the two models estimation is calculated by:

$$APE=\left|\frac{Observation-Estimation}{Observation}\right|\times 100\% \tag{8}$$

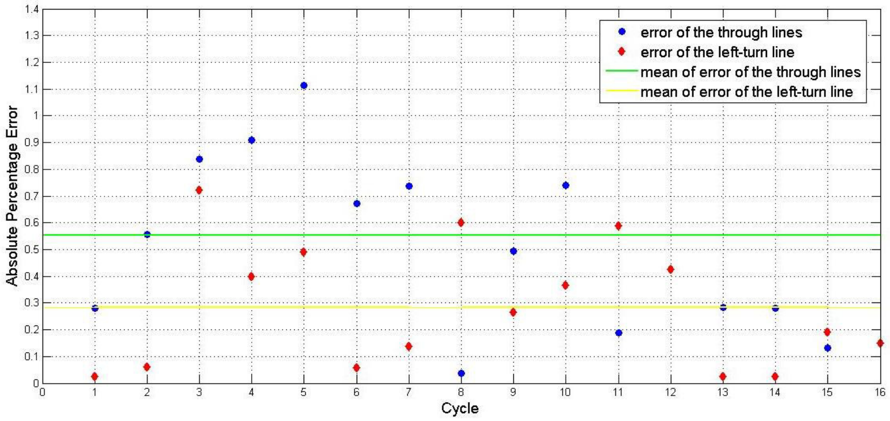
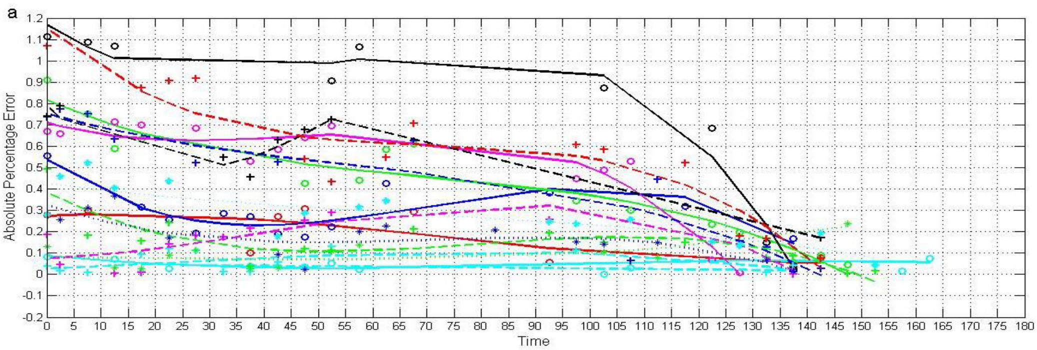
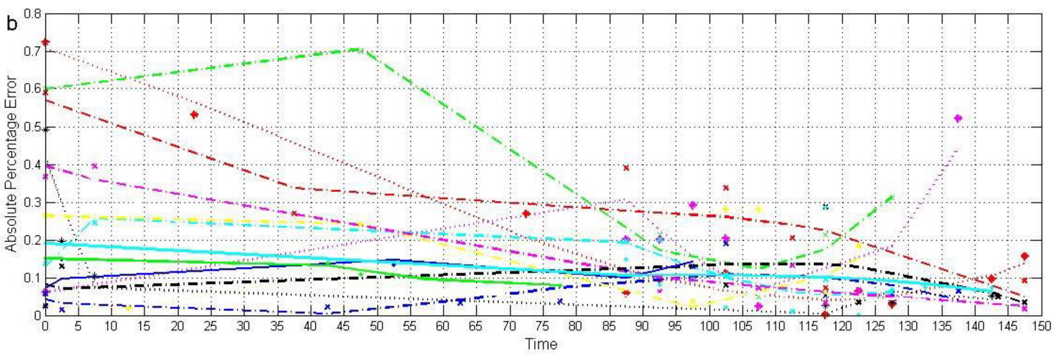


Fig 4. APE of the HCM 2000 estimation

Fig.4 shows the HCM 2000 estimation of each cycle for both the through and left-turn approaches. In addition, an average value of the APE of the two approaches is also calculated. There are 11 instances out of 31 (35.5%) APE output where either the through and the left-turn lines was lower than 20%. There smallest APE of the through and left-turn lines is 2.55%. There are 10 instances out of 31(32.3%) APE output was higher than 50%. The largest APE of the through and left-turn lines is 111.27%. The average values of the two approaches are 55.45% and 28.31% respectively. The absolute percentage error of the estimation of HCM is high.



(a) APE of each cycle for the through approach



(b) APE of each cycle for the left-turn approach

Fig 5. Values and fitted curves of the two methods APE of each cycle: (a) the through approach profiles;(b) the left-turn approach profiles

To study the results of the estimation of the two methods, we set up a cubic curve-fitting equation deduces to describe the APE of the estimation of the two methods. As is shown in Fig.5, the interval is set to 5 seconds for statistical data collection. As there is no floating car available at the start of each cycle, all the spots when time=0 represent the result of the HCM 2000 estimation. Other spots represent APE of alternative method using the data of floating cars arrived at different time of each cycle and the curves are the fitting curves based on the spots. Part (a) shows the APE of each cycle for the through approach while Part (b) illustrates that for the left-turn approach. In Part (a), there is a downward trend of the APE fitting curves by the time. This means the later a float car arrives in the queue the more accurate estimation can be gotten and the method developed in this paper can get more precise estimation of MBQL than the HCM2000 method. In Part (b), 12 instances out of 16 (75%) APE fitting curves have the same trend with Part (a), while the downward trend of others (25%) is reversed. As developed based on the HCM 2000 model, the method in this paper does not apply to shaky arriving traffic either. It is supposed that the unstable arrive flow is the reason why the APE of the left-turn approach is not stable as the through approach.

5. Conclusion

This study developed a new calculation method of HCM 2000 that can automate the calculation of maximum back of queue length data at signalized intersections. The method uses floating car data and data from loop on road to calculate MBQL. Compared with HCM 2000 method, the method has calculated MBQL at a more accuracy level as well as could be applied in most practical level of service evaluation applications. The later float cars arrive in the queue, the more accuracy estimation of the developed method can be obtained. However, shaky arrive flow will lead to unexpected result as the downward trend reverses.

As is tested in real-time environment, the proposed method can provide more precise estimation than HCM 2000. Without manual observation, the method can be applied in larger scope of area. For the method to work, data of floating cars and loop need to be stored precisely.

Acknowledgements

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